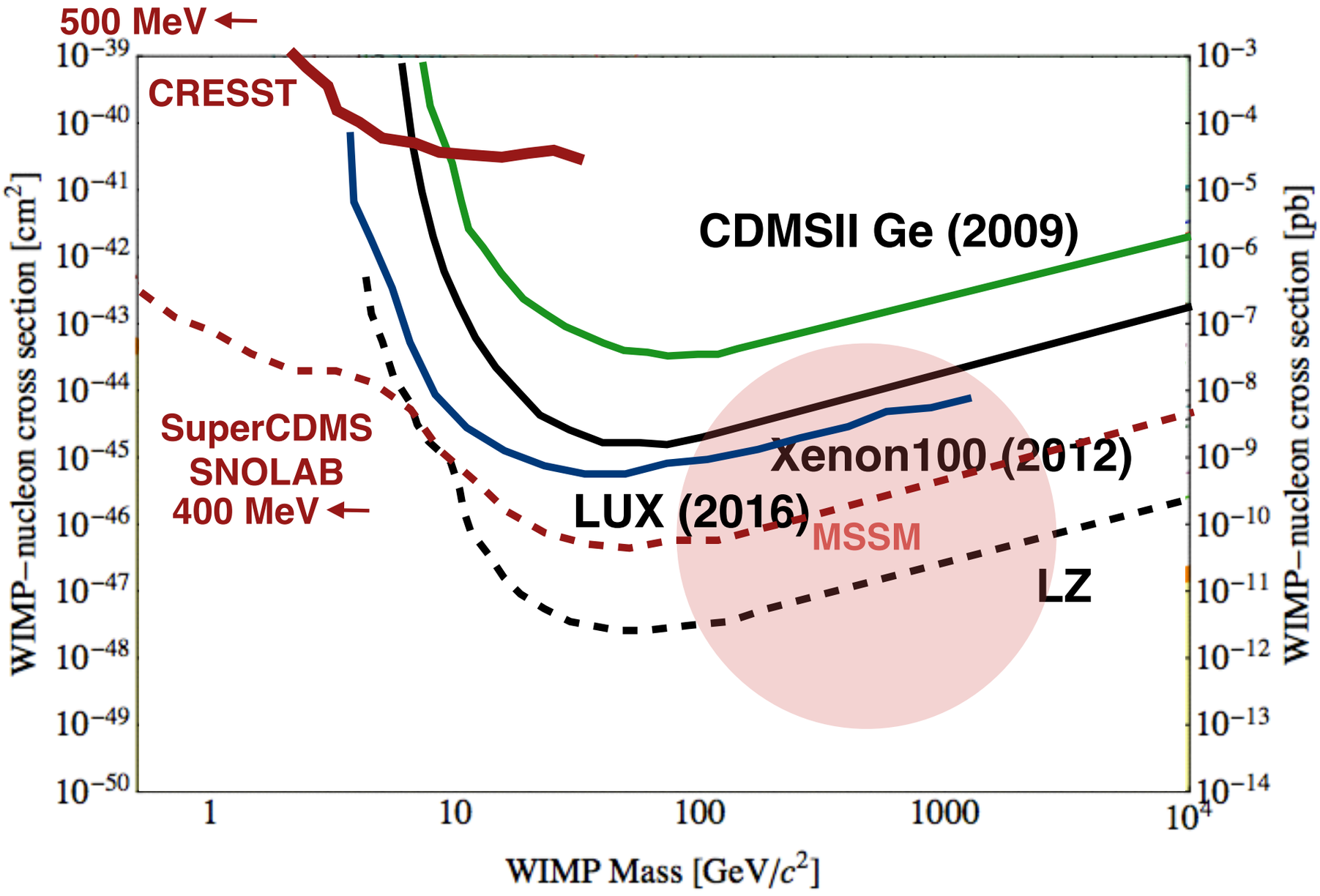
Exploring the sub-GeV Dark Matter Frontier with SENSEI

Tien-Tien Yu (CERN & UOregon)
for the collaboration

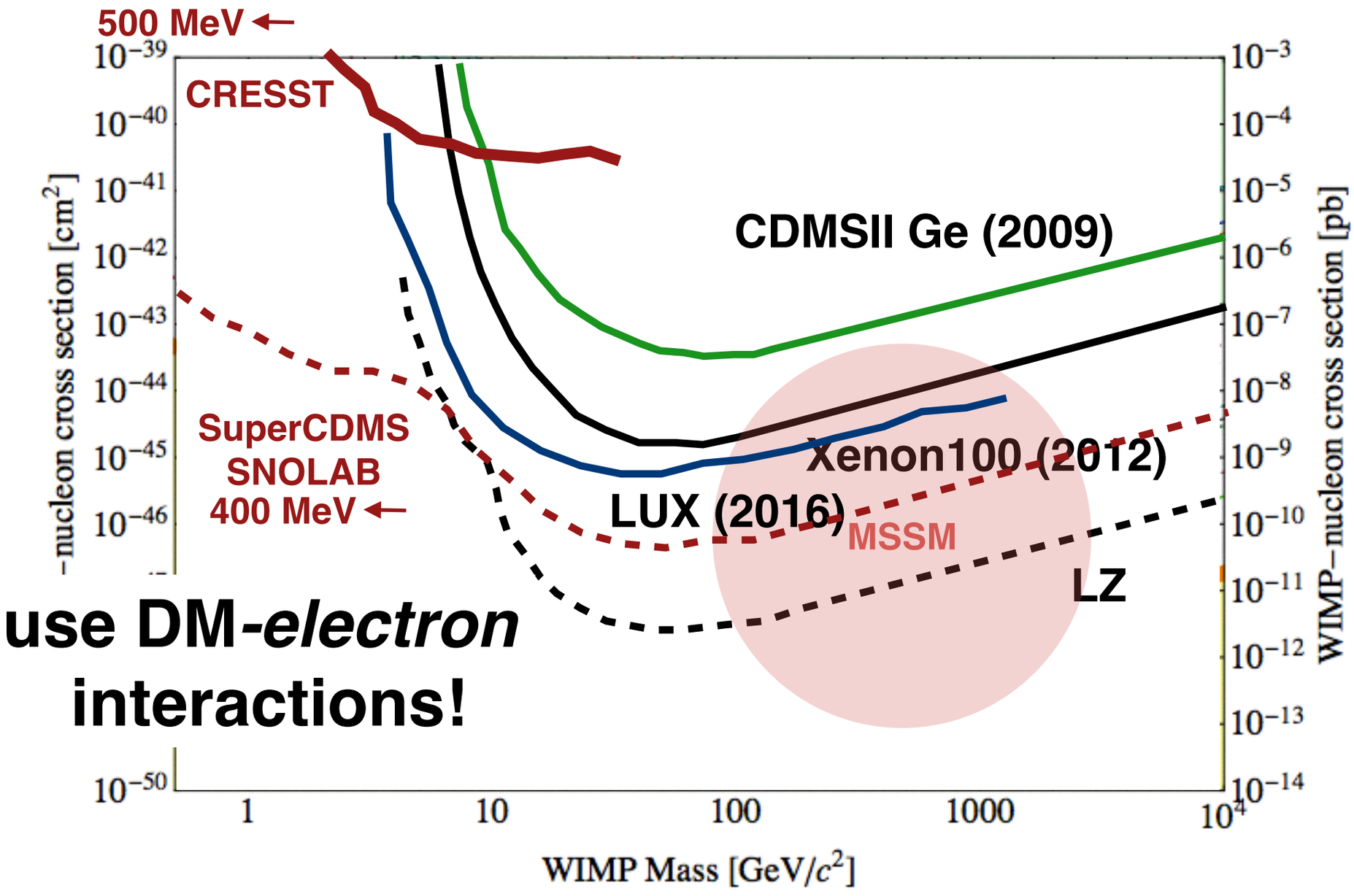
UCLA Dark Matter 2018

February 23, 2018

DM-nucleon elastic scattering



DM-nucleon elastic scattering



use DM-*electron* interactions!

SENSEI

Sub-**E**lectron-**N**oise **S**kipper CCD **E**xperimental **I**nstrument

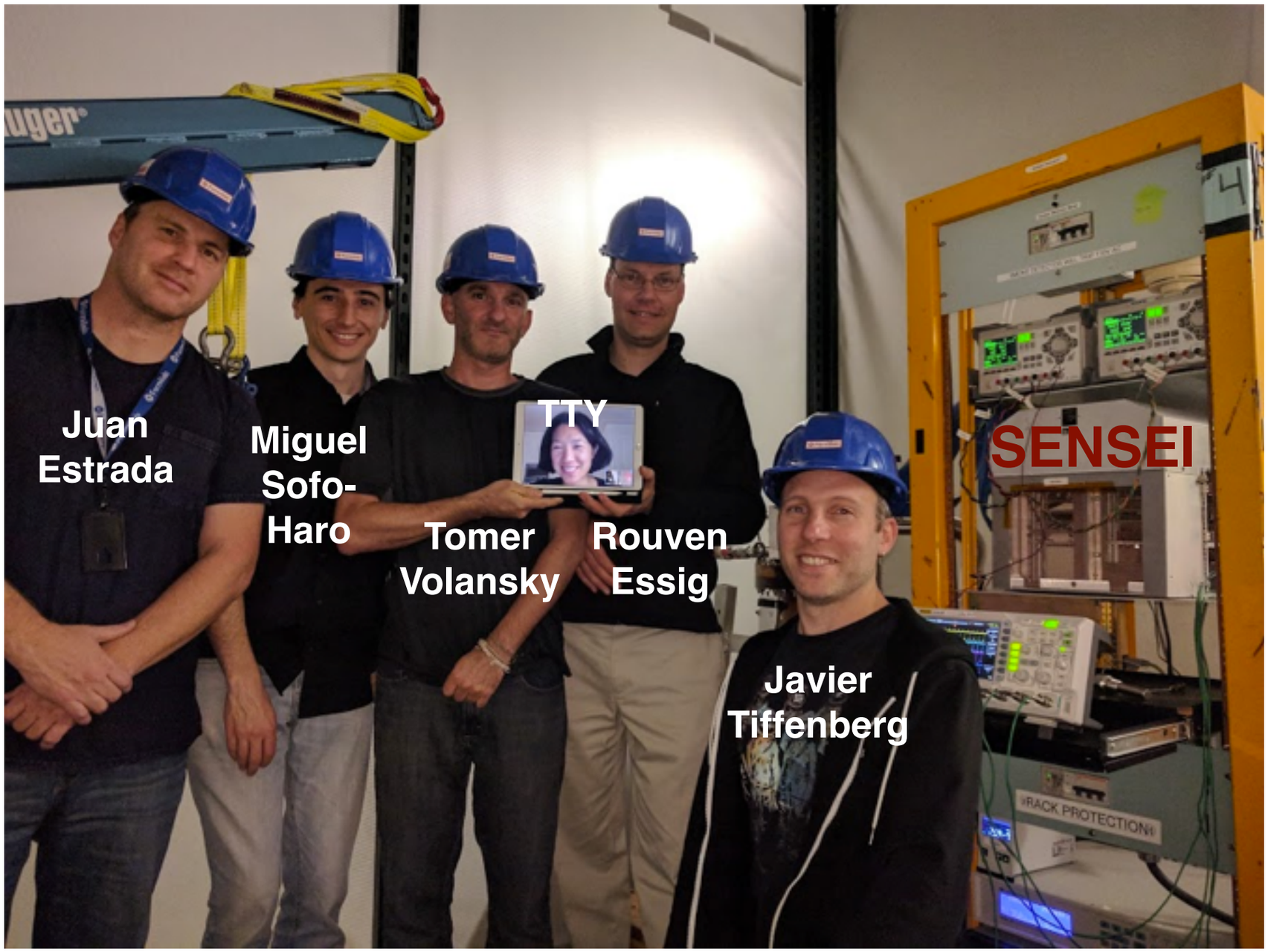
***Objective**: Develop a CCD-based detector with single-electron sensitivity using SkipperCCDs produced by LBL MSL*

Main Goals:

- Build the first working detector using Skipper-CCDs.
- Validate the technology for DM and neutrino experiments.
- Probe DM masses down to MeV masses using electron-recoil
- Probe ALPs and Dark Photons down to eV masses through bosonic absorption

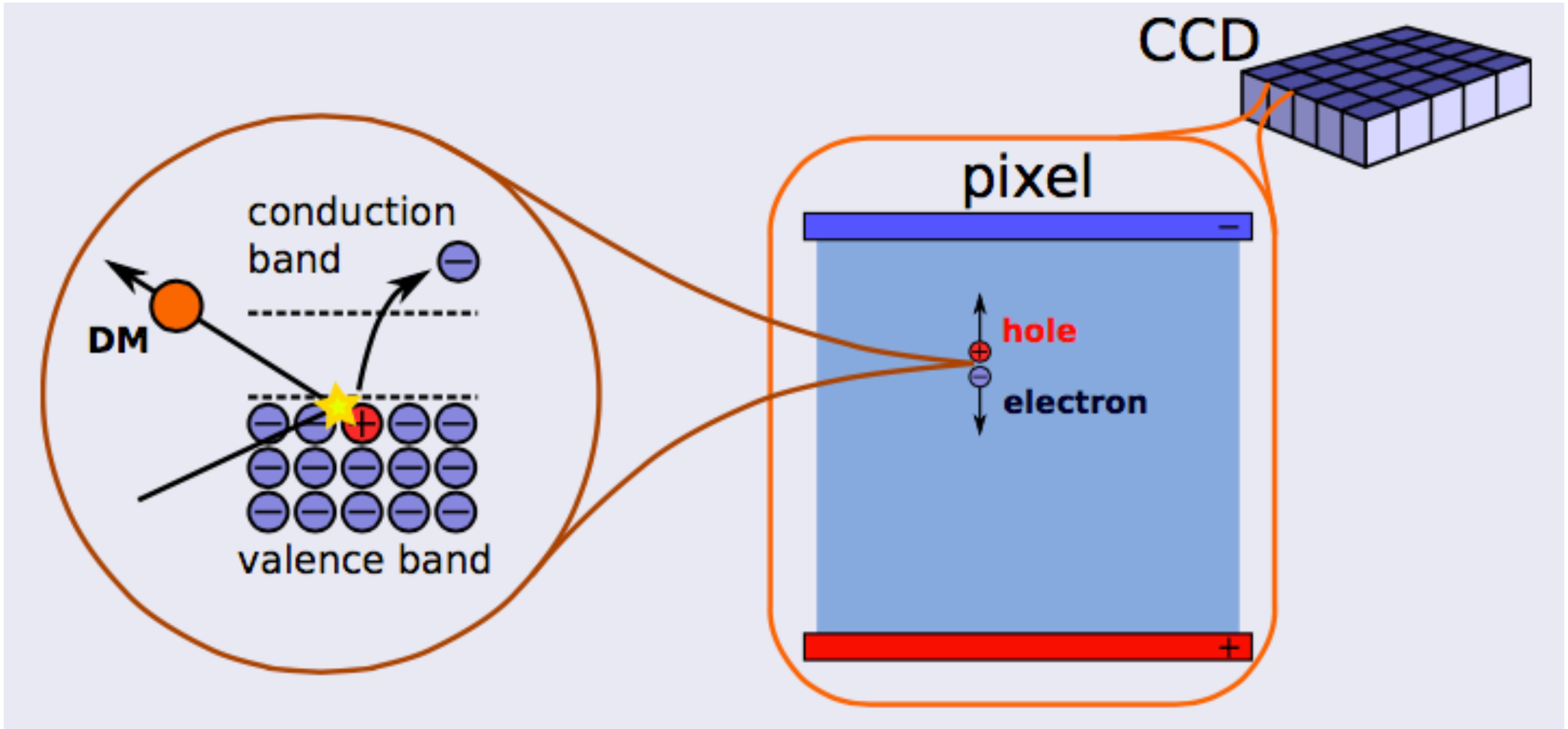
SENSEI

Sub-**E**lectron-**N**oise **S**kipper CCD **E**xperimental **I**nstrument



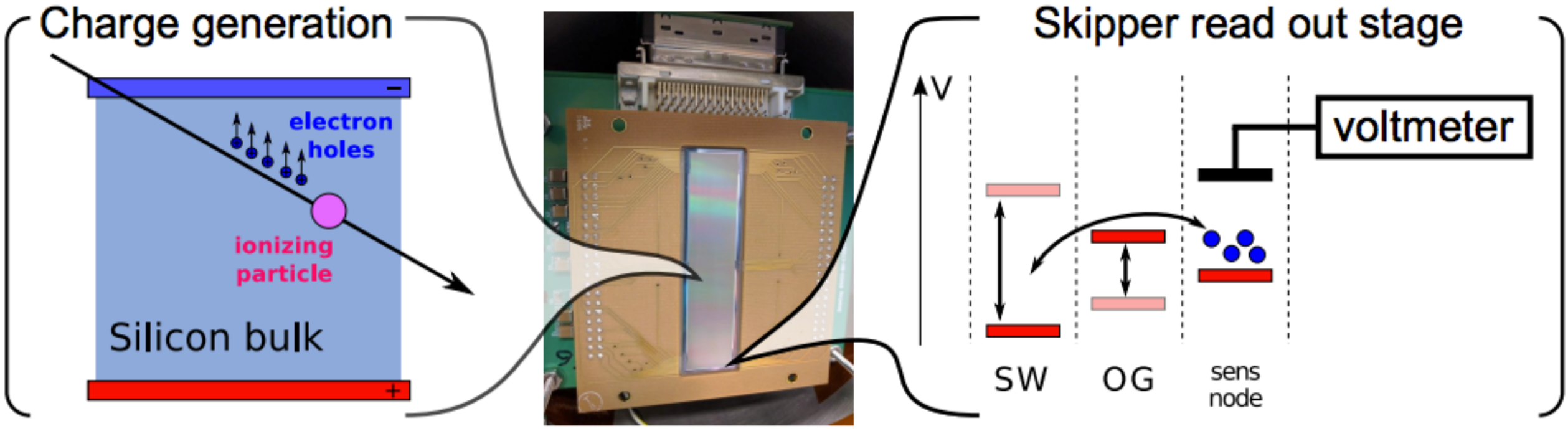
+ Guillermo Fernandez Moroni
+ Michael Crisler

silicon CCD detector



requires very low noise!
two sources: readout, dark current

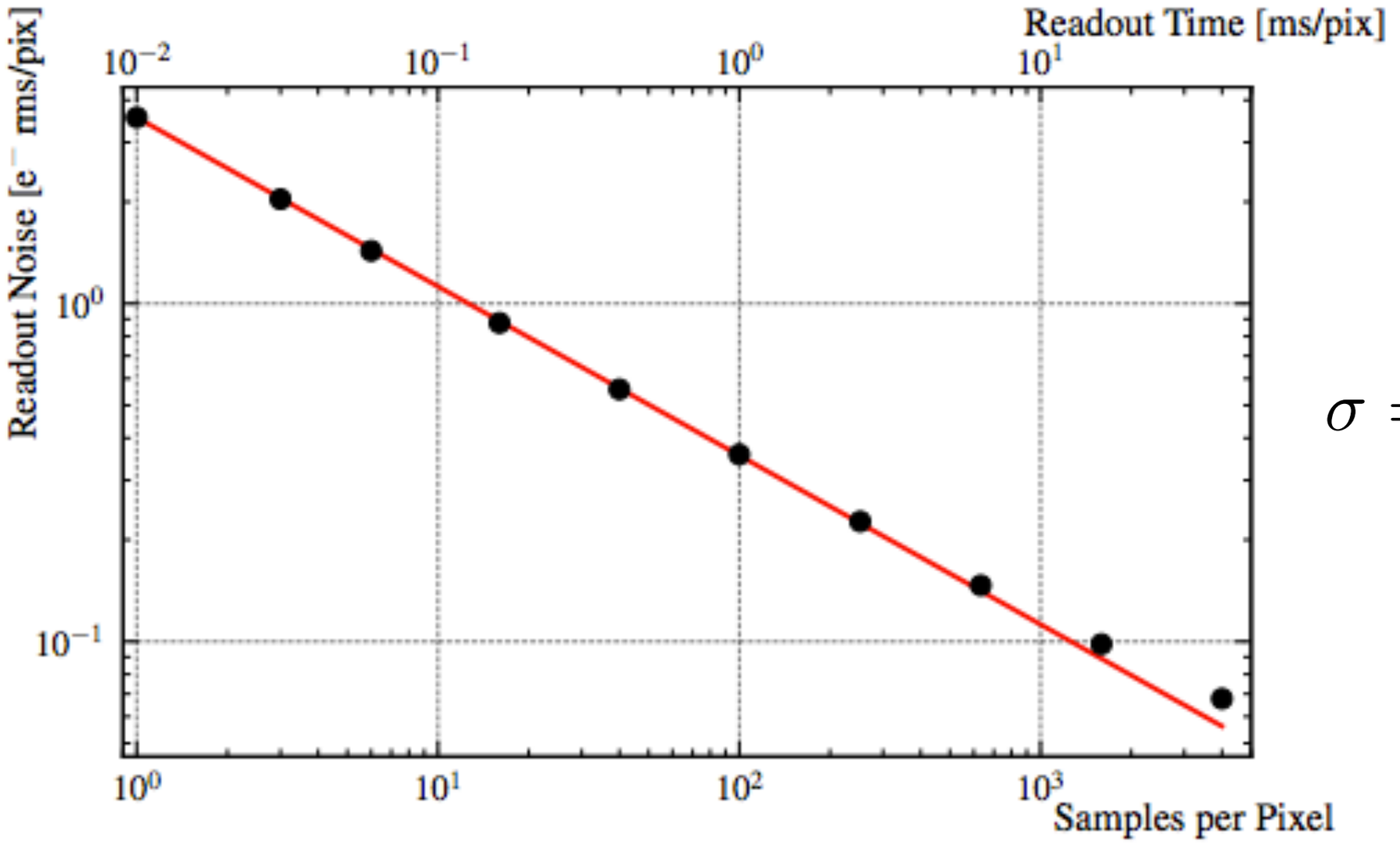
skipper readout



non-destructive readout ➡ possible to have multiple readouts

Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, Volansky, TTY [1706.00028]

readout noise



$$\sigma = \frac{\sigma_1}{\sqrt{N}}$$

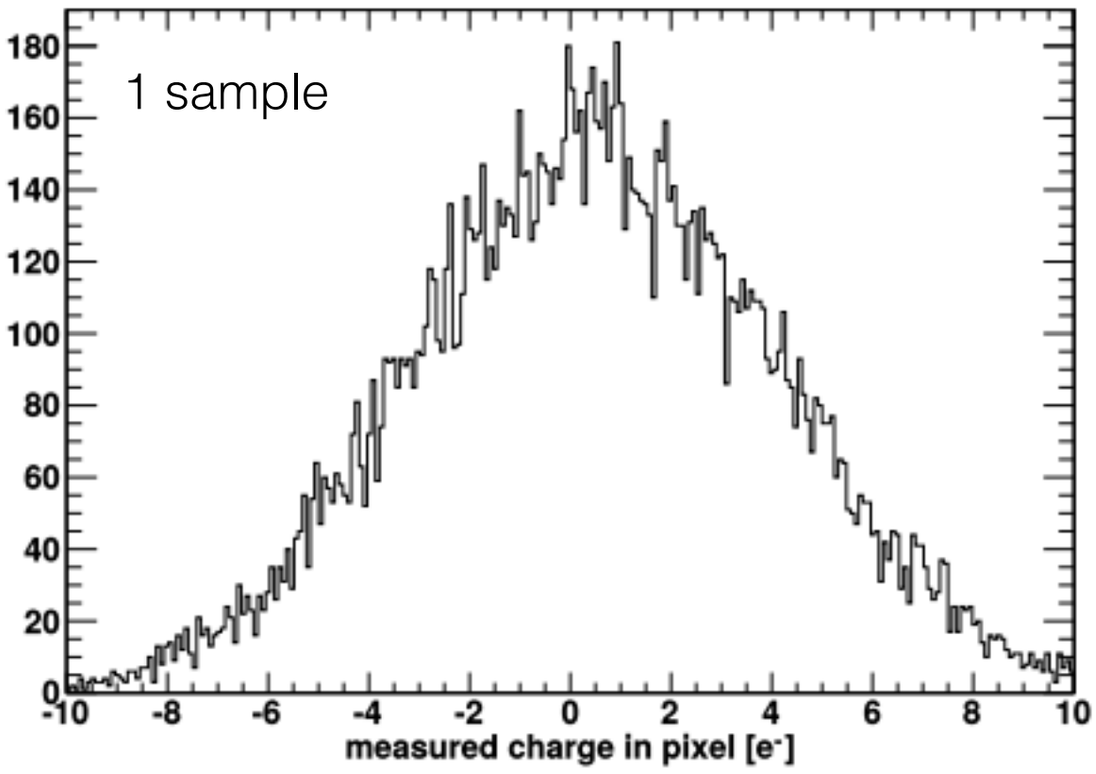
reduce readout noise by increasing readout time

Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, Volansky, TTY [1706.00028]

skipper readout

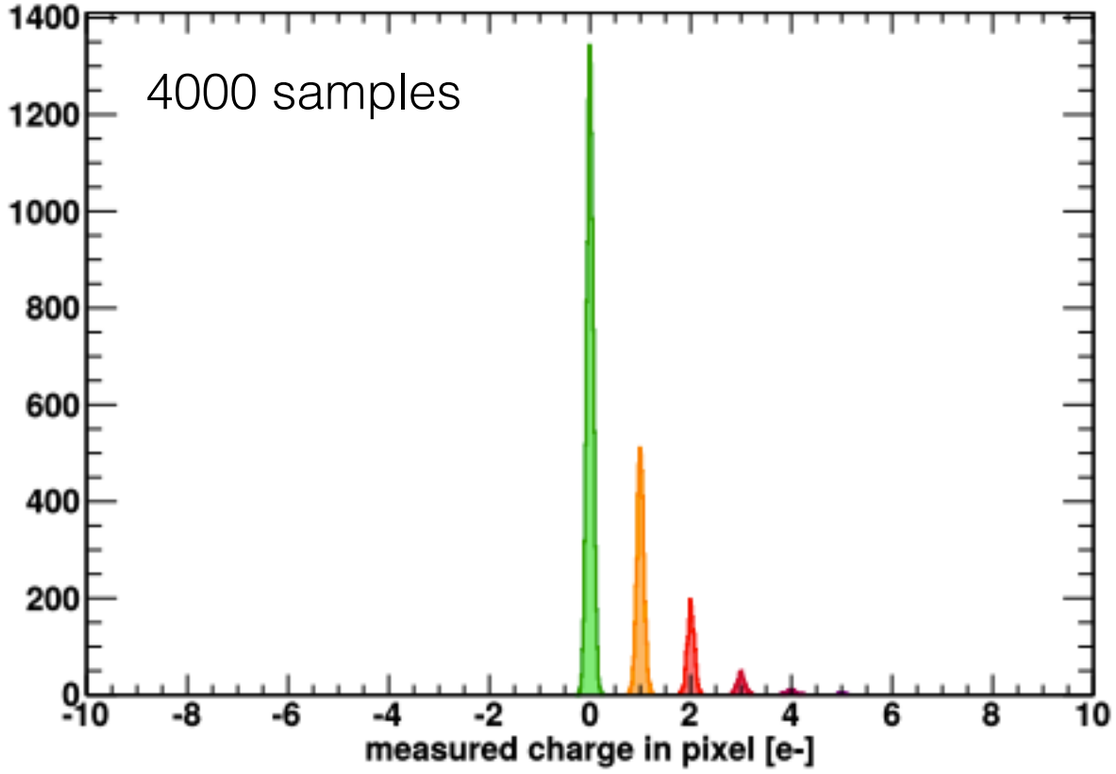
standard CCD

Readout-noise: 3.5 e RMS



skipper CCD

Readout-noise: 0.06 e RMS



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skipper readout

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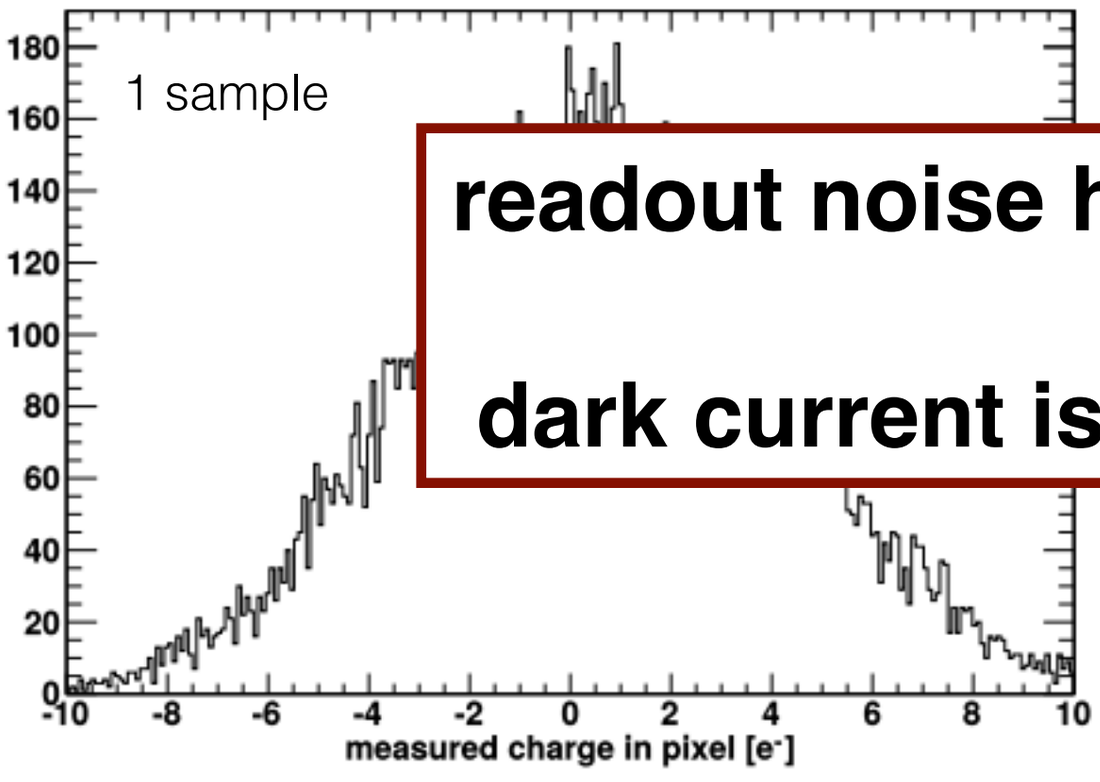

skipper CCD

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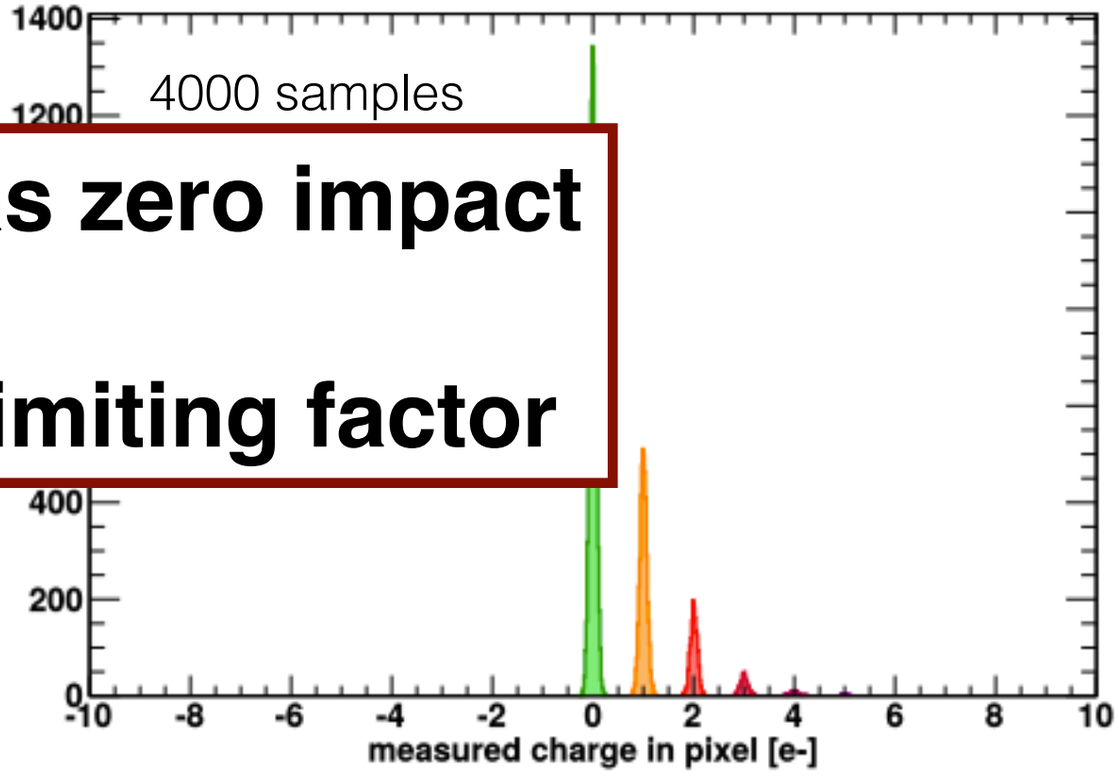


readout noise has zero impact

dark current is limiting factor

Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, Volansky, TTY [1706.00028]

dark current

dark current [e^-/pix/day]	**$\geq 1e^-$** [pix]	**$\geq 2e^-$** [pix]	**$\geq 3e^-$** [pix]
10^{-3}	**1×10^{8}**	**3×10^{3}**	**7×10^{-2}**
10^{-5}	**1×10^{6}**	**3×10^{-1}**	**7×10^{-8}**
10^{-7}	**1×10^{4}**	**3×10^{-5}**	**7×10^{-14}**

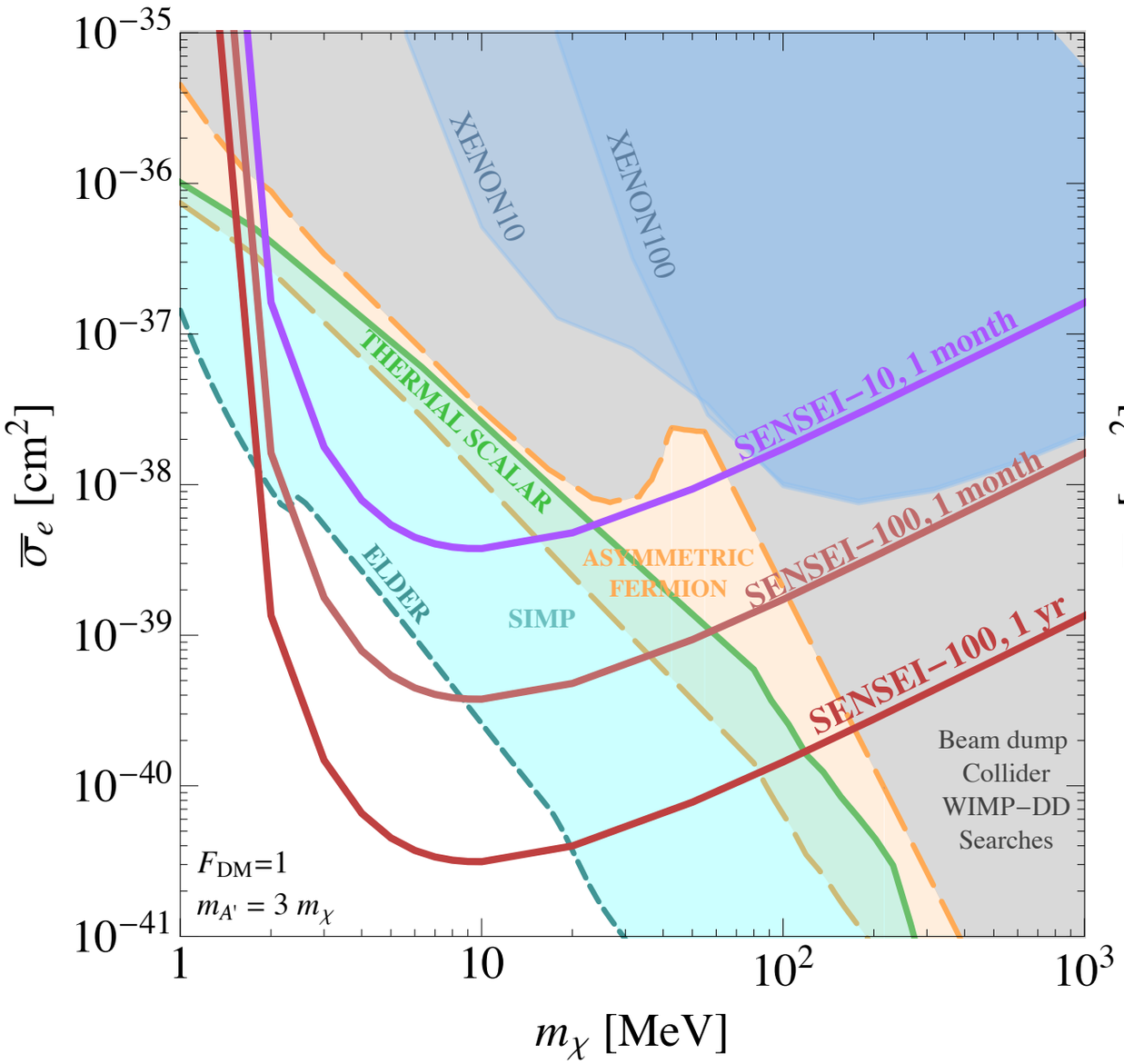
dark current

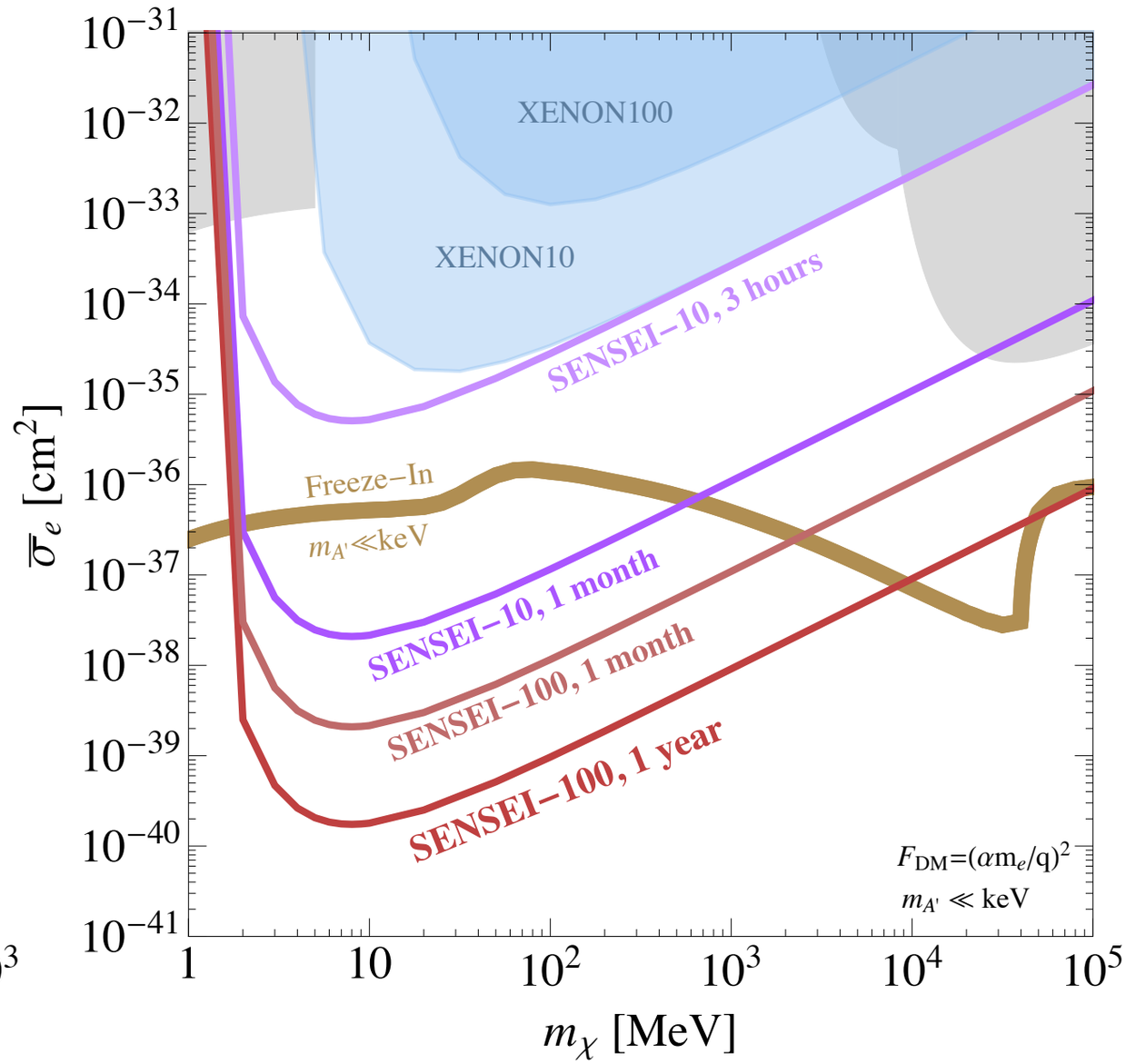
dark current [e^-/pix/day]		≥1e^- [pix]	≥2e^- [pix]	≥3e^- [pix]
measured ⟶ [arXiv:1611.03066]	10^{-3}	$1x10^{8}$	$3x10^{3}$	$7x10^{-2}$
	10^{-5}	$1x10^{6}$	$3x10^{-1}$	$7x10^{-8}$
theory ⟶ prediction	10^{-7}	$1x10^{4}$	$3x10^{-5}$	$7x10^{-14}$

SENSEI with a 2-electron threshold is a zero-background experiment!

physics potential

electron scattering





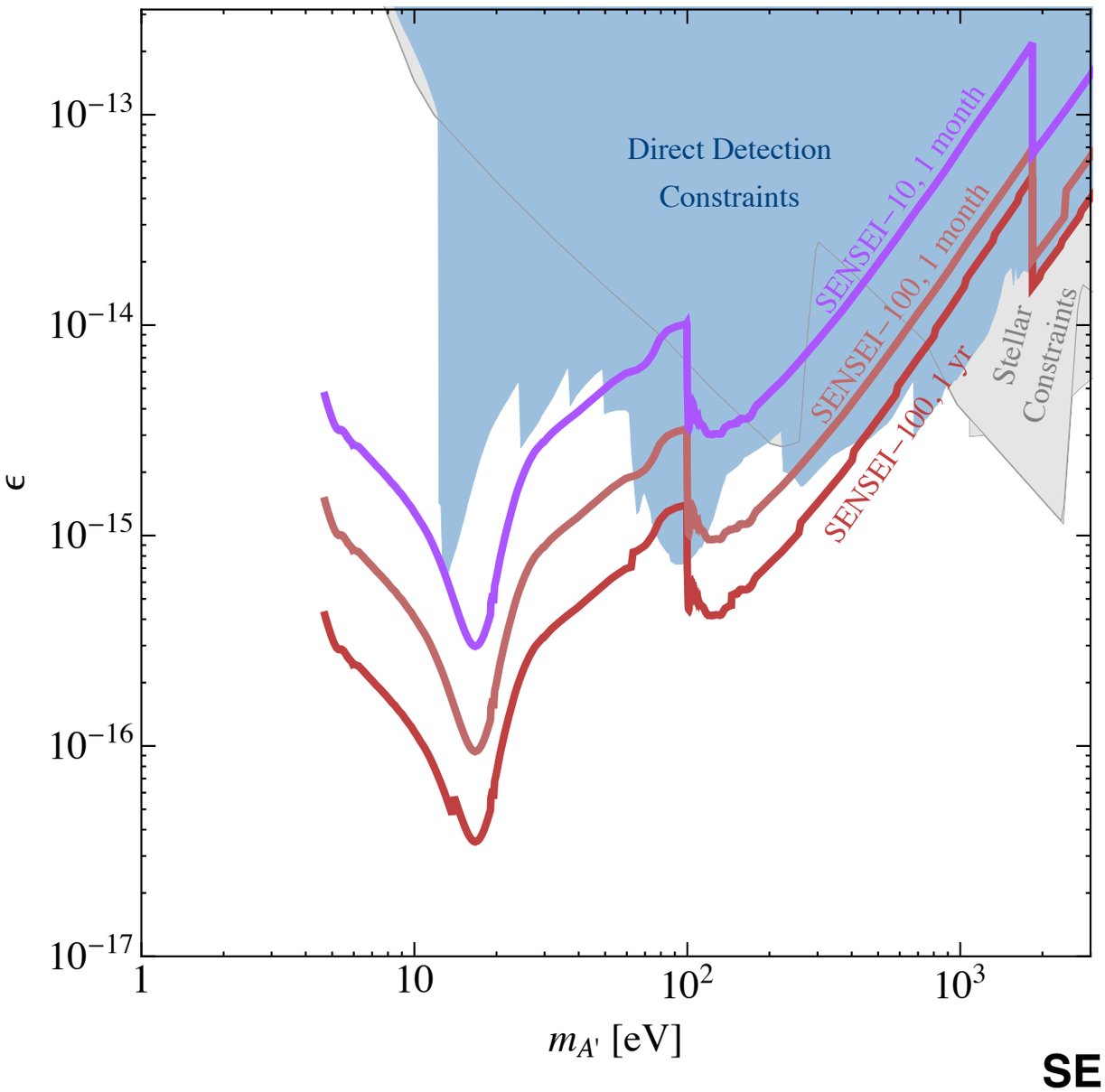
based on:

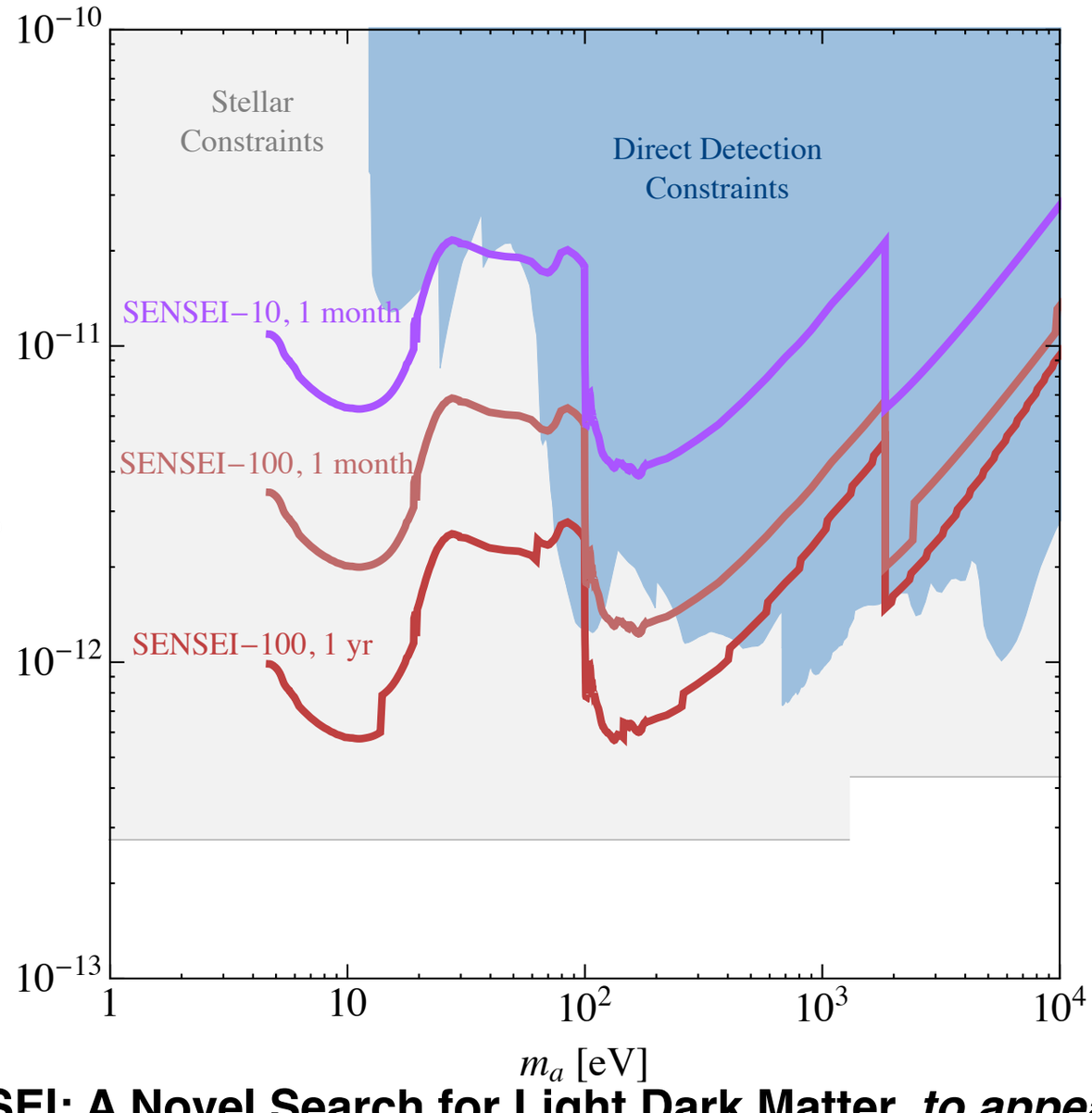
SENSEI: A Novel Search for Light Dark Matter, *to appear*

Essig, Volansky, TTY [1703.00910], Essig, Fernandez-Serra, Mardon, Soto, Volansky, TTY [1509.01598]

physics potential

bosonic absorption





SENSEI: A Novel Search for Light Dark Matter, *to appear*

based on: Bloch, Essig, Tobioka, Volansky, TTY [1608.02123]

timeline

2016

LDRD funded,
fabrication of SkipperCCD
prototype

2017

testing of prototype @MINOs,
received funding from HSF and FNAL
to design and build 100g detector

2018

assembly and testing of 10g
detector at MINOS,
take data

2019

deploy 100g detector at
deeper underground site

2020

analyze 10g data,
continue data taking with
100g detector

2021

analyze 100g data

timeline

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100g detector

2021

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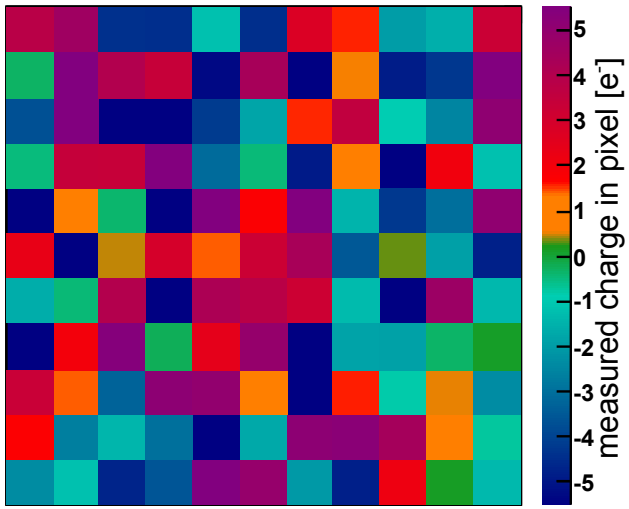
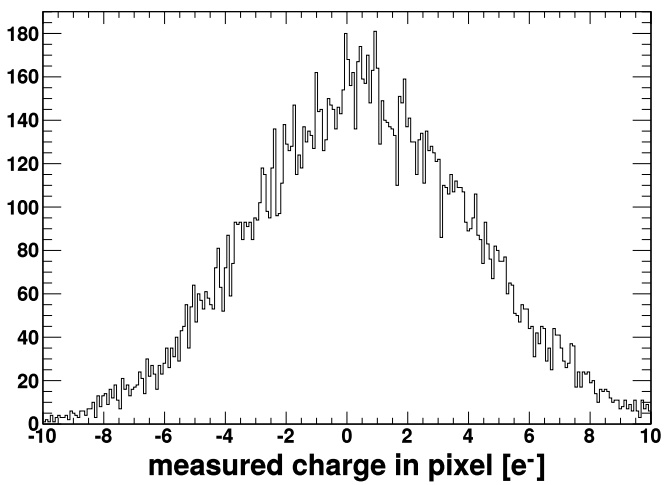
extras

Counting electrons: 0, 1, 2..

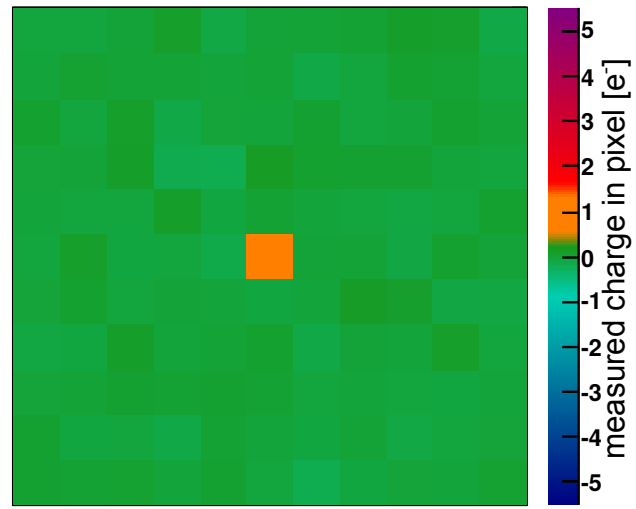
Standard CCD mode: charge in each pixel is measured once



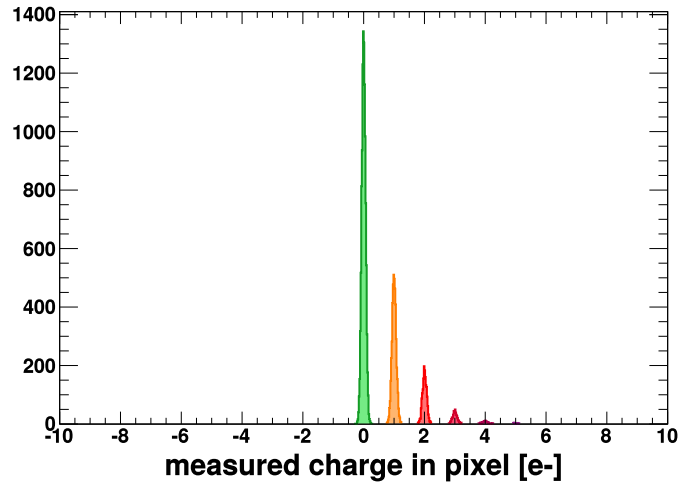
Readout-noise: 3.5 e RMS



New Skipper CCD: charge in each pixel is measured multiple times

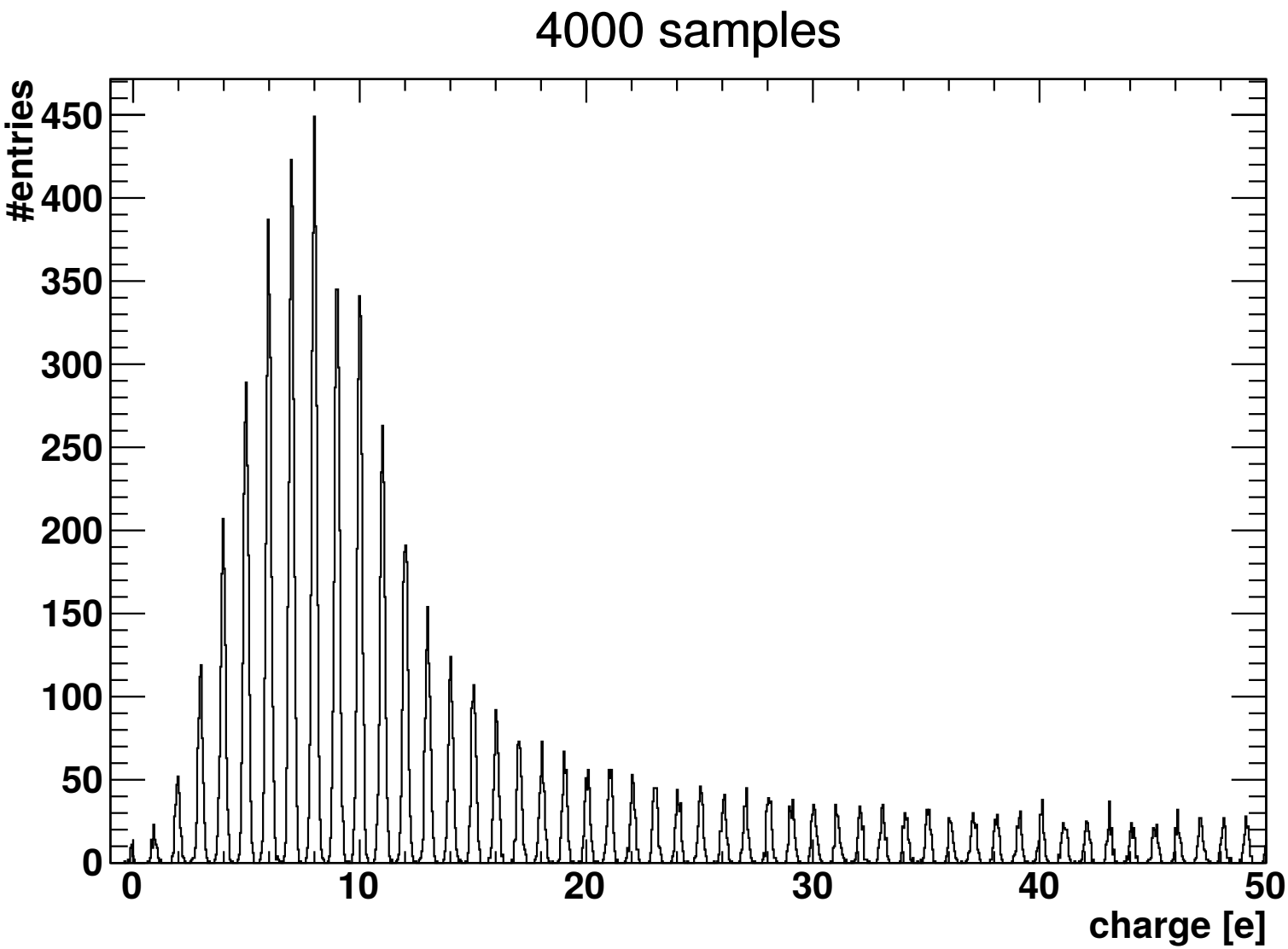


Readout-noise: 0.06 e RMS



Fermilab

Counting electrons: ..48, 49, 50..

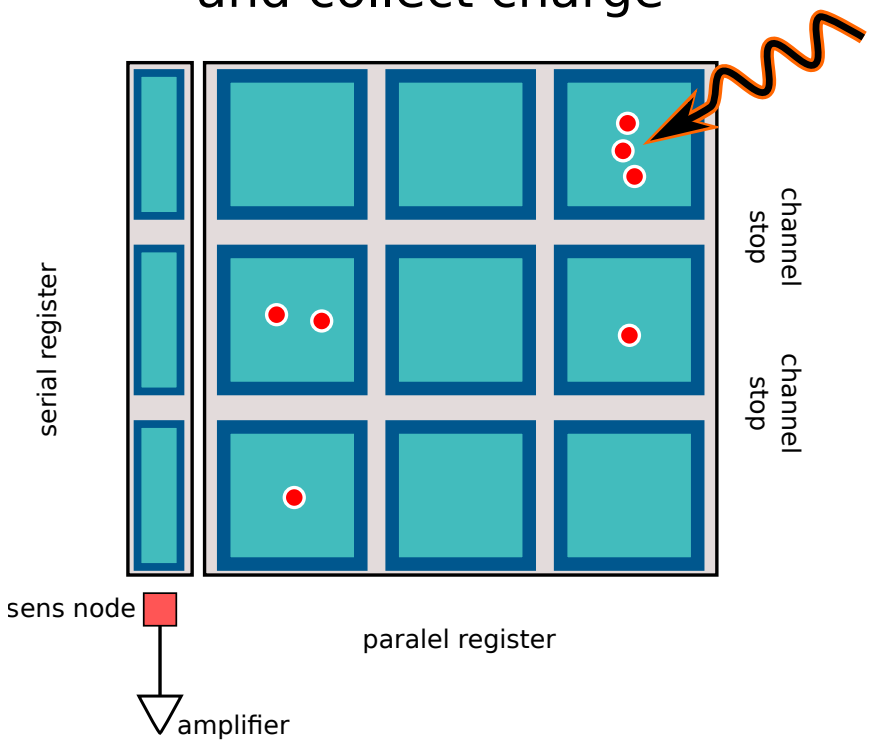


Fermilab

CCD: readout

3x3 pixels CCD

Expose the CCD to particles
and collect charge



CCD: readout

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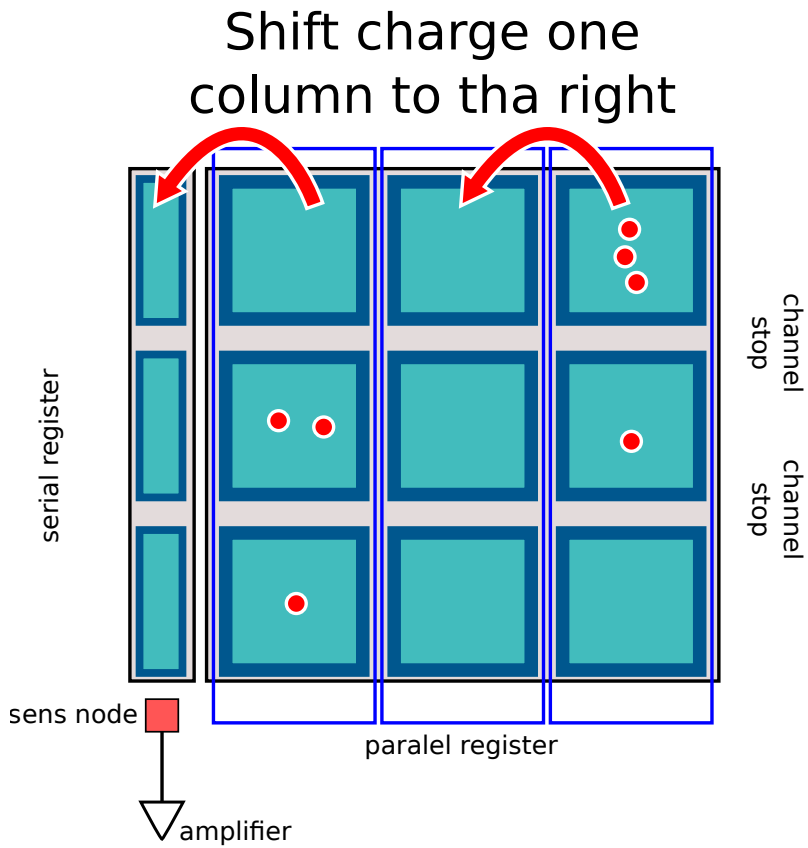
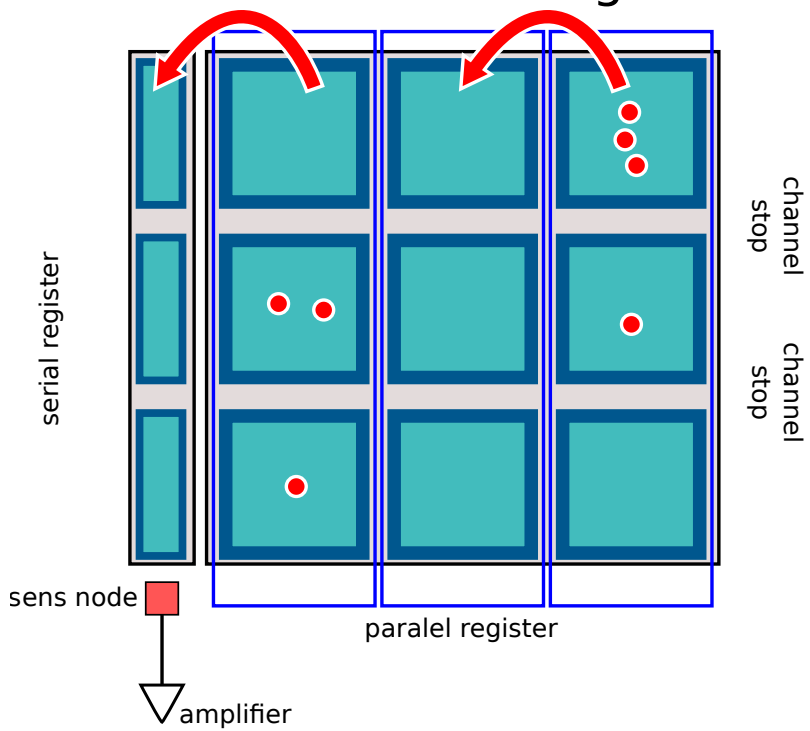


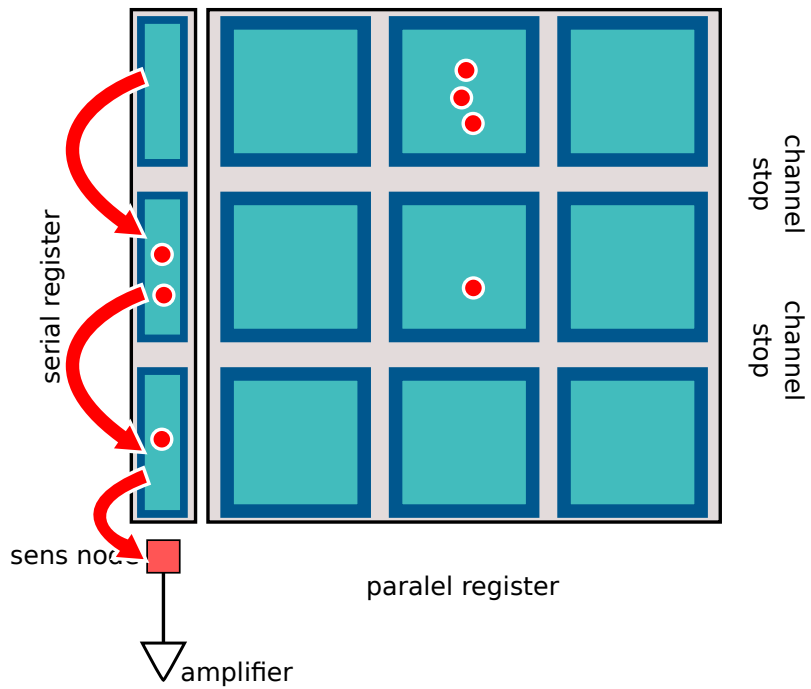
CCD: readout

3x3 pixels CCD

Shift charge one column to tha right



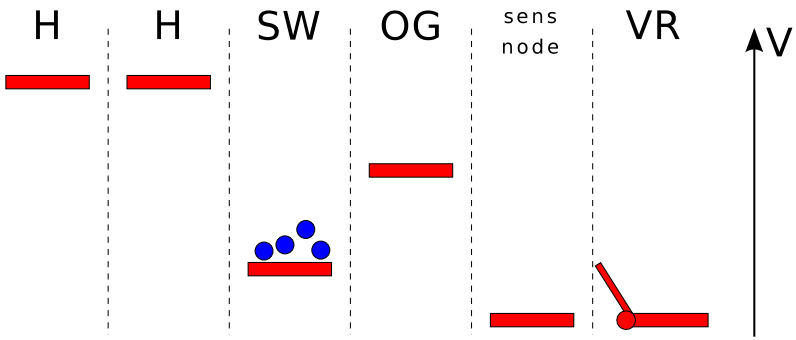
Shift charge in serial register one pixel down (3 times)

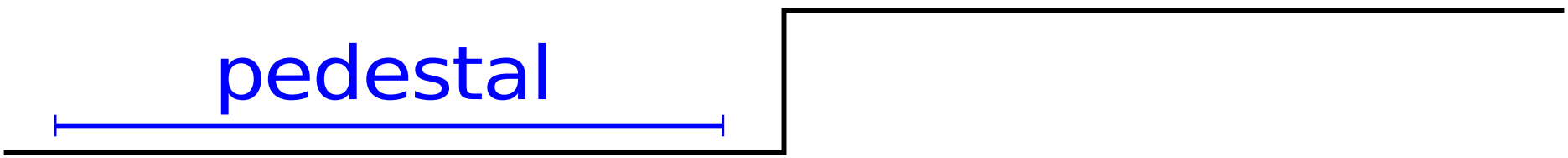


capacitance of the system is set by the SN: C=0.05pF$\rightarrow$ 3μV/e

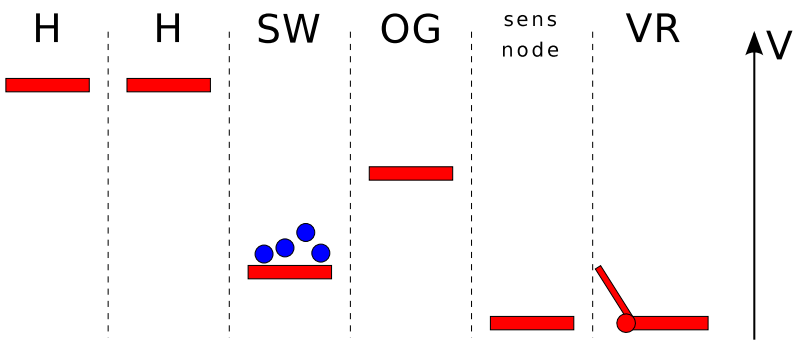
Fermilab

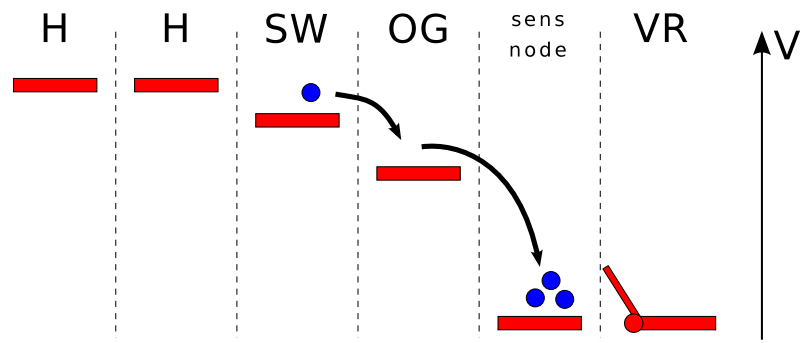
CCD: readout

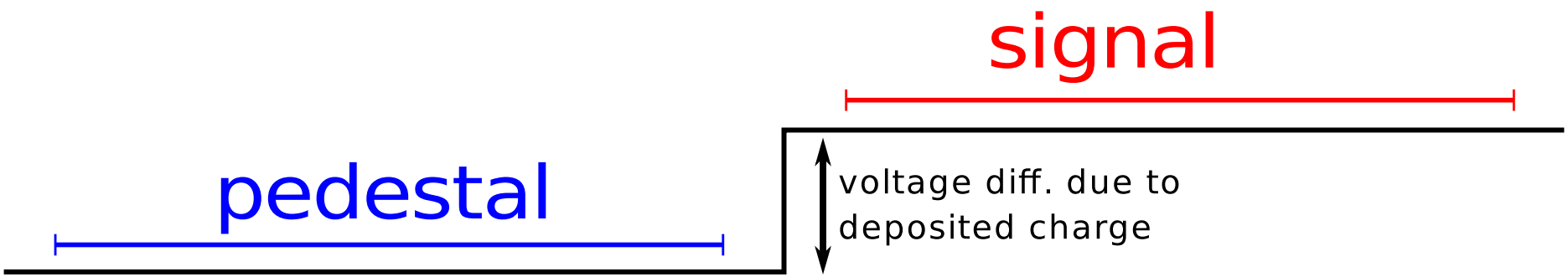




CCD: readout

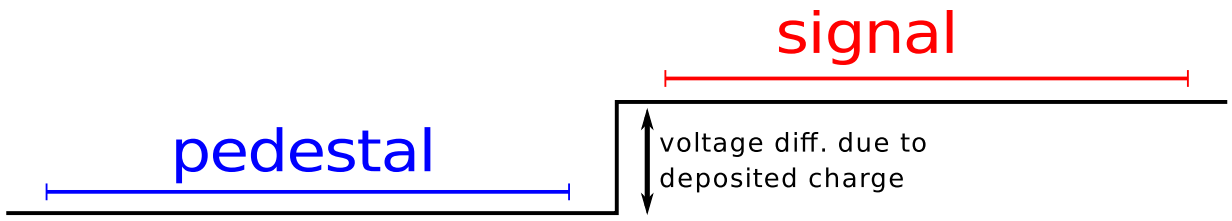

H
H
SW
OG
sens
node
VR
V


H
H
SW
OG
sens
node
VR
V

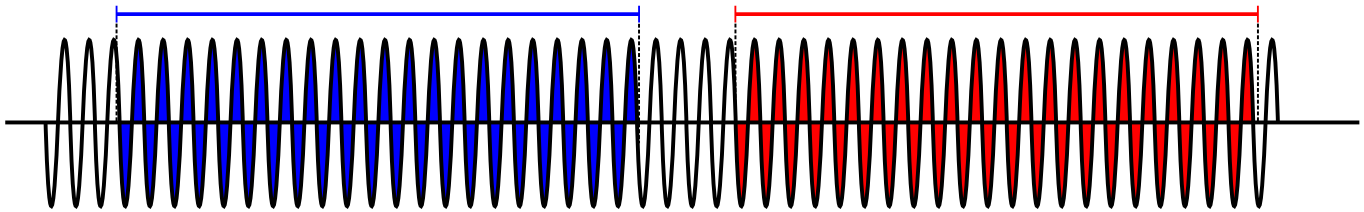

signal
pedestal
voltage diff. due to
deposited charge

CCD: readout

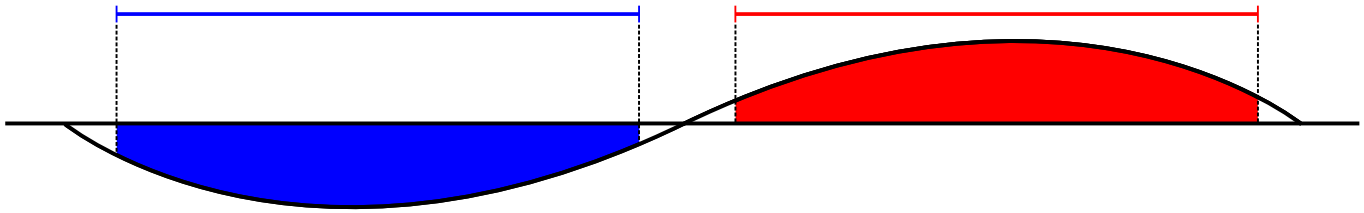
pixel charge measurement



high frequency noise

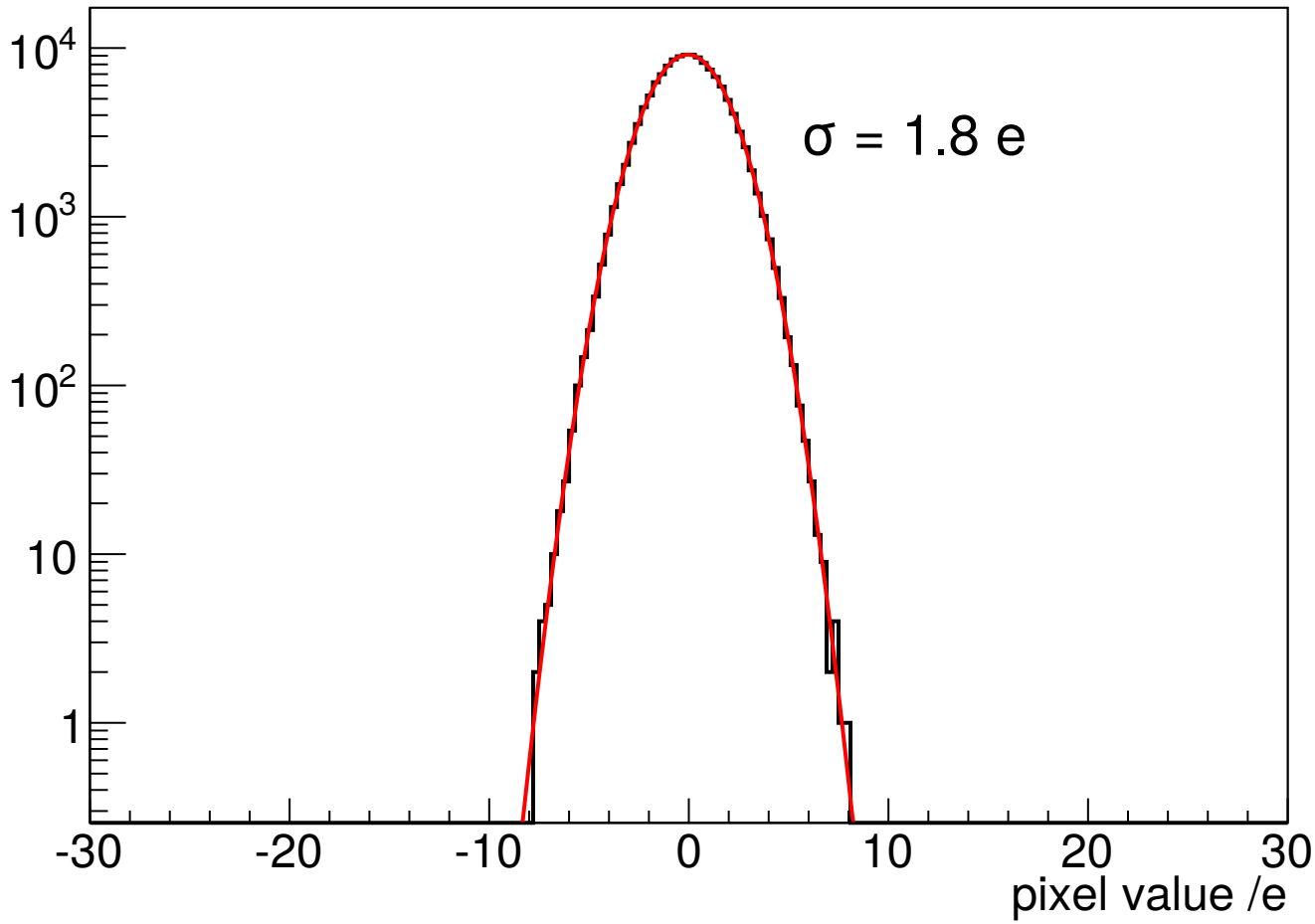


low frequency noise



excellent for removing high frequency noise but sensitive to low frequencies

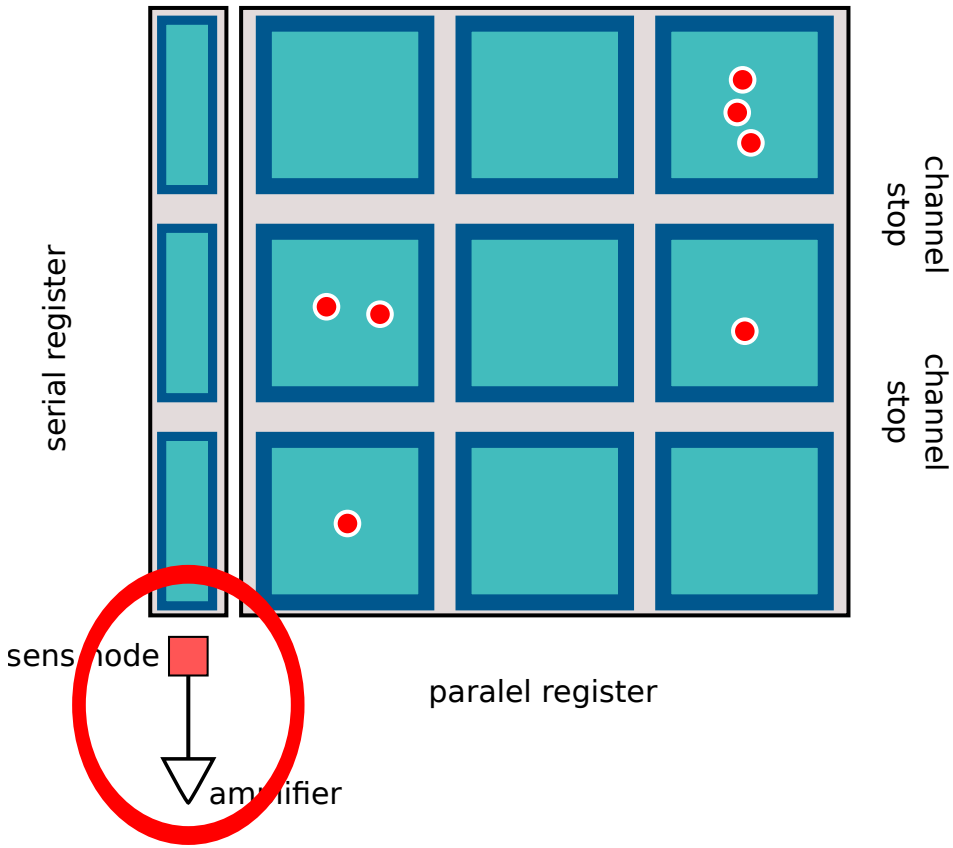
Readout noise: empty pixels distribution, regular scientific CCD



2 e^- readout noise roughly corresponds to 50 eV energy threshold

Fermilab

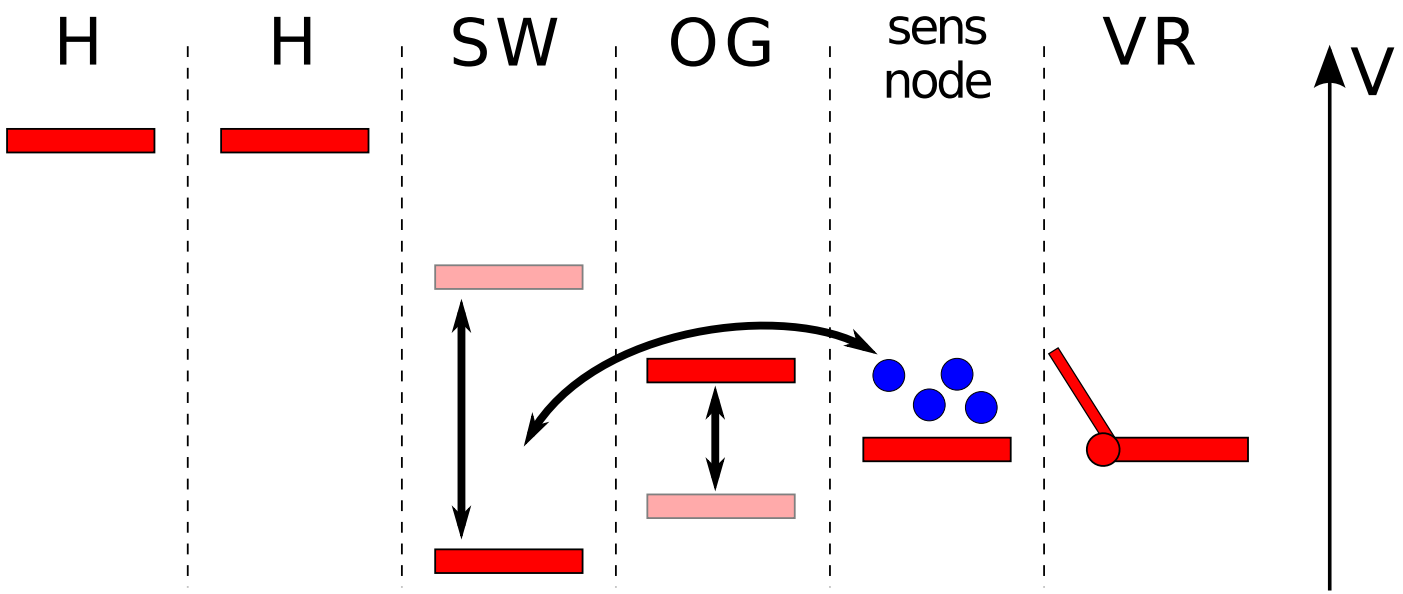
Lowering the noise: Skipper CCD



Only the readout stage is modified

Lowering the noise: Skipper CCD

- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  Pixel value $= \frac{1}{N}\Sigma_i^N$ **(pixel sample)**$_i$
- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)



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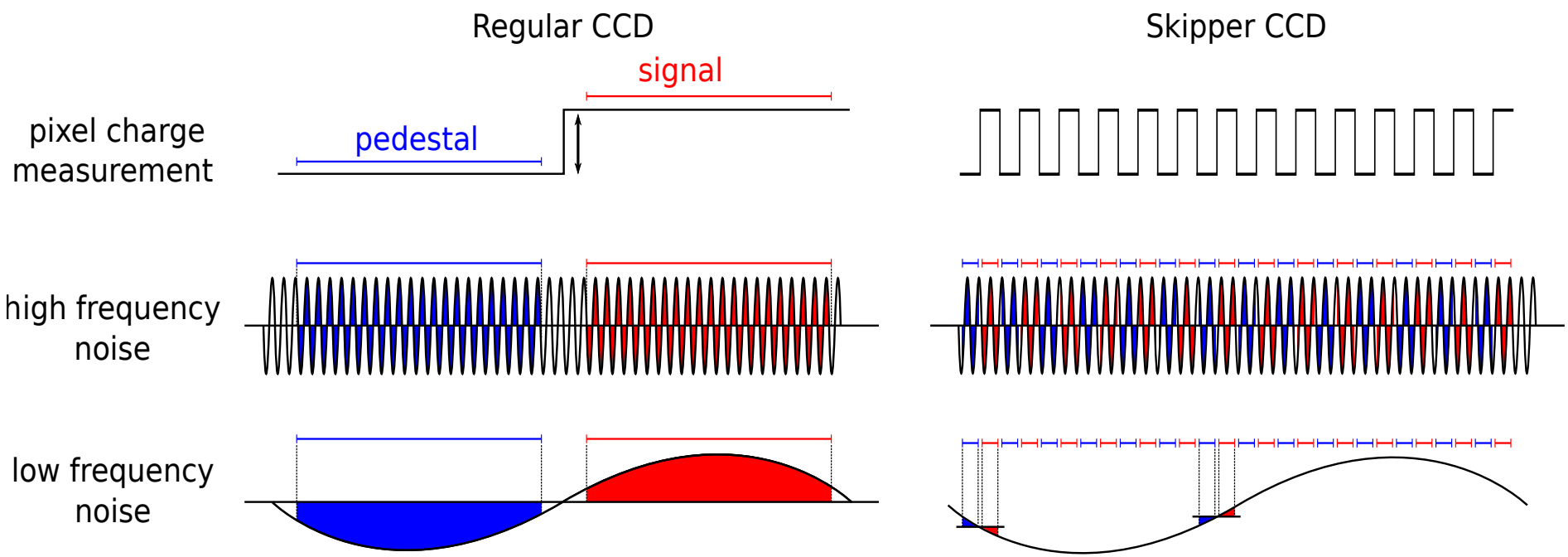

Fermilab